Invasive Plant Science and Management 2010 3:276–285

Characterizing Pathways of Invasive Plant Spread to Alaska: II. Propagules from Imported Hay and Straw

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The extent and nature of spread of exotic plant species to and within Alaska by shipment of hay and straw was studied. The amounts of hay and straw imported into Alaska and the amounts and types of seed in imported and locally produced hay and straw was determined We purchased alfalfa hay, wheat straw, ryegrass straw, and timothy hay produced in Washington and Oregon (WA–OR) and locally produced straw and hay. The hay and straw were shaken over screens, and the remaining fines were mixed with sterile potting soil and incubated in the greenhouse. Forty-nine plant species were identified from hay and straw, nine of which are ranked as invasive in Alaska, including downy brome, foxtail barley, hare barley, narrowleaf hawksbeard, and quackgrass—a prohibited weed in Alaska. The number of seeds ranged from 0 to 6,205 seeds kg^{-1}, with an average of 585 seeds kg^{-1}, and the number of species ranged from 0 to 12, with an average of 4.2 species per bale. Crop seed comprised a large proportion of the germinated seeds in ryegrass straw, wheat straw, and timothy/brome hay (98, 78, and 62%, respectively), but was less prevalent (ranging from 0 to 38%) in the other three hay and straw crop types. Hay and straw from Alaska contained more total seeds and species than hay and straw from WA-OR, but the difference was not significant when only weed seed was used in the analysis. Alaska-grown timothy/brome hay contained significantly more total seed than alfalfa hay and wheat straw from WA–OR and Alaska-grown barley straw. The grower or distributor of the hay and straw also influenced the number of seeds and species among some crop types. Results of this study document that large numbers of alien plant species are transported by movements of hay and straw into and within Alaska.

Nomenclature: Alfalfa, *Medicago sativa* L.; downy brome, *Bromus tectorum* L.; foxtail barley, *Hordeum jubatum* L.; hare barley, *Hordeum murinum* L. ssp. *leporinum* (Link) Arcang.; narrowleaf hawksbeard, *Crepis tectorum* L.; quackgrass, *Elymus repens* (L.) Gould; ryegrass, *Lolium* spp.; timothy, *Phleum pratense* L.; wheat, *Triticum aestivum* L.

Key words: Pathways, hay, straw, invasive plants, indicator species.

Weed diversity and abundance are increasing worldwide despite control efforts, and new management paradigms might be needed (Forcella and Harvey 1983). Prevention is the most powerful and cost-effective tool in combating the spread of weeds (Davies and Sheley 2007; DiTomaso 2000; Radosevich et al. 1997; Reichard 1997). One dollar spent on prevention and early control of nonindigenous species can save $17 in future expenditures occurring without early intervention (Office of Technology Assessment of U.S. Congress 1993). Tools for prevention include use of weed-free crop and revegetation seed, feed, soil, mulches, and equipment, as well as creation and enforcement of seed and other plant material laws or quarantines (Holt 2004).

Strategies to prevent weed invasion and to respond quickly to new introductions could be more efficiently designed and employed if more were known about invasion pathways (Ruiz and Carlton 2003). Species often take predictable pathways to reach new areas (Forcella and Harvey 1988; Mack 2003; Thomas et al. 2007; Van der Muelen and Sindel 2008), but the pathways can differ in the number and types of seeds traveling and the likelihood of establishment once species arrive (Ruiz and Carlton 2003). The number of plant propagules traveling in a pathway is important because propagule pressure (frequency and size of introductions) is a critical determinant of introduction success (Colautti et al. 2006; Ruiz and Carlton 2003).

Alaska is relatively free from nonnative plants (Carlson and Shephard 2007; Rejmanek and Randall 1994), but in

DOI: 10.1614/IPSM-D-09-00041.1

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Interpretive Summary

Hay and straw were studied to determine whether its shipment is a significant pathway for the importation and spread of weed seed in Alaska. Local vendors were surveyed in 2004 and 2005 to determine the amounts and types of hay and straw sold. The hay and straw types were alfalfa hay, timothy hay, ryegrass straw, and wheat straw from Oregon and Washington; and barley straw and timothy/brome hay from Alaska. Three bales of each hay or straw type were purchased, one quarter of each bale was shaken over screens, and the fine material that passed through the screens was mixed with sterile potting soil in flats and kept moist in a heated greenhouse. Seedlings were counted and identified as they germinated. Forty-nine plant species were identified from hay and straw, nine of which are ranked as invasive in Alaska, including downy brome, foxtail barley, hare barley, narrowleaf hawksbeard, and quackgrass—a prohibited weed in Alaska. There was an average of 13,827 seeds and 4.2 species per bale. Crop seed comprised an average 64% of the germinated seeds from all hay and straw bales but was highly variable, ranging from 0% in alfalfa hay to 98% in ryegrass straw. Hay and straw from Alaska contained more seeds and species than hay and straw from WA–OR, but there was no difference when only weed seed was used in the analysis. Alaska timothy/brome hay contained more seeds than WA–OR alfalfa hay and wheat straw and Alaska barley straw. The grower or distributor that produced or brokered the hay and straw also affected the number of seeds and species for some crop types, reflecting differences in weed management and other farming practices. Hay and straw shipment is a significant pathway for the movement of weed seeds into and within Alaska.

recent years, the rate of exotic plant introductions has increased dramatically. Carlson and Shephard (2007) determined that the rate of new introductions of exotic taxa in Alaska's flora increased from roughly one species per year from 1941 to 1968 to three species per year from 1968 to 2006, mirroring the threefold increase in human population in Alaska since 1968, as well as the increase of goods shipped to the state. Preventing new introductions of alien plant species into Alaska should be feasible given its geographic isolation with limited points of entry for goods into the state by container ship, truck, and airfreight. Alaska invasive plant prevention efforts could be maximized by targeting the most important pathways. For this reason we began a series of studies of pathways for seed movement into Alaska to determine the relative importance of each.

We previously reported on the size and nature of the pathway from soil imported with ornamentals in containers or in root balls (Conn et al. 2008). Fifty-one nonnative plant species were found, including one prohibited species and nine other species classified as invasive in Alaska. The number of propagules was greatest in larger pots or rootballs containing unsterilized soil. Ornamentals from some producers had no associated weed propagules, whereas soils from ornamentals grown by other producers had high numbers of exotic plants.

In 2005, we initiated a study to determine the importance of imported and locally produced hay and straw as a pathway for movement of exotic plant species into and within Alaska. Grass and alfalfa (*Medicago sativa* L.) hay are primarily used in Alaska for horse feed, winter feed for cattle, and sled dog bedding. Grain hay (straw) is used primarily for sled dog bedding, mulch for erosion protection, and cattle feed. Alaska growers produce smooth bromegrass (*Bromus inermis* Leyss.), timothy (*Phleum pratense* L.), and bluegrass (*Poa* spp.) hay; and spring barley (*Hordeum vulgare* L.) and oat (*Avena sativa* L.) straw. Between 2000 and 2007, grass hay production ranged from 16,500 to 30,000 tons yr^{-1} and straw ranged from 300 to 2,000 tons yr^{-1} (Benz et al. 2008). In productive years, nearly all in-state demand for hay and straw can be met by local production, but in years with drought or too much precipitation during harvest, a considerable portion of demand must be met through importation of hay and straw. Alfalfa does not grow well in Alaska, so all alfalfa hay is imported.

Hay and straw containing weeds are thought to be a pathway for movement of exotic species, and numerous countries, states, and land management agencies have taken prudent preventative actions (USDA Forest Service, Pacific Northwest Region 2009). The North American Weed Management Association (NAWMA) in the United States has established a program to satisfy the demand for forage and mulch that does not contain seed of certain invasive plant species (NAWMA 2006). The program established standards for inspecting and certifying that fields are free of weed species contained on their designated noxious weed list.

Despite the widespread conviction that transportation of hay and straw is an important means for long-distance weed dispersal, there is little direct evidence of this (Clines 2005). Plant invasions stemming from hay and straw being used as packing material have been reported, but these have largely been conjectural (Mack 2003). For example, Dewey (1897 *in* Mack 2003) theorized that downy brome (*Bromus tectorum* L.) and poverty brome (*Bromus sterilis* L.) infestations in Denver were associated with straw packaging. Similarly, there is circumstantial evidence that hay and straw for forage is a significant pathway for long-distance seed dispersal. Hay and straw were reported vectors for the movement and dispersal of yellow burrweed (*Amsinckia* spp.; Erkelenz et al. 1990) and branched broomrape (*Orobanche ramosa* L.; Secomb 2006) in Australia. Cole (1983) and Marion et al. (1986) suggested that invasive plant species in the United States were introduced by hay brought into wilderness areas for pack stock. Clines (2005) reported that yellow star thistle (*Centaurea solstitialis* L.) in California established from bales of straw used for erosion control, Canada thistle (*Cirsium arvense* L. Scop.) established along a highway directly after mulching with

Table 1. Frequency of occurrence (%) and mean number of seeds (kg^{-1}) for weed species found in hay and straw in Alaska.[a,b,c]

		Frequency of occurrence						Mean number of seeds						
		Alaska		WA–OR				Alaska		WA–OR				ANOVA
Scientific name	Common name	TBH	BS	AH	TH	RS	WS	TBH	BS	AH	TH	RS	WS	Pr > *F*
		%						No. seeds kg^{-1}						
Achillea millefolium L.	Common yarrow	5	0	0	0	0	0	0.72	0	0	0	0	0	0.58
Agrostis scabra Willd.	Rough bentgrass	11	27	0	0	0	0	0.23 b	2.3 c	0 a	0 a	0 a	0 a	**0.001**
Alopecurus geniculatus L.	Water foxtail	0	0	0	0	17	0	0 a	0 a	0 a	0 a	0.17 b	0 a	**0.01**
Alopecurus pratensis L.	Meadow foxtail	5	0	0	0	0	0	1.1	0	0	0	0	0	0.58
Amaranthus retroflexus L.	Redroot pigweed	0	0	13	20	0	14	0	0	0.32	47	0	0.15	0.22
Anthemis cotula L.	Mayweed chamomile	0	0	0	0	0	14	0	0	0	0	0	0.08	0.15
Avena sativa L.	Oat	0	0	0	0	0	5	0	0	0	0	0	0.01	0.65
Brassica rapa L.	Birdsrape mustard	11	18	0	5	0	5	0.40	0.14	0	0.03	0	0.34	0.77
Bromus inermis Leyss.	Smooth brome	26	0	0	5	0	5	32	0	0	0.52	0	0.02	0.21
Bromus tectorum L.	Downy brome	0	0	47	45	0	33	0	0	1.3	63	0	1.40	0.50
Capsella bursa-pastoris (L.) Medik.	Shepherd's-purse	11	73	7	45	17	19	0.11 ab	54 ab	0.11 ab	439 bc	0.79 ab	0.89 a	**0.03**
Cardamine hirsuta L.	Hairy bittercress	0	0	0	0	17	0	0	0	0	0	0.34	0	0.21
Cerastium glomeratum Thuill.	Sticky chickweed	11	0	0	5	50	0	43	0	0	0.04	14	0	0.45
Chenopodium album L.	Common lambsquarters	11	18	0	5	0	0	0.07	0.25	0	0.51	0	0	0.69
Crepis tectorum L.	Narrowleaf hawksbeard	0	18	0	0	0	0	0	3.1	0	0	0	0	0.09
Descurainia sophia (L.) Webb. ex Prantl	Flixweed	0	0	13	10	17	14	0	0	0.15	7.3	1.0	0.79	0.57
Echinochloa crus-galli (L.) Beauv.	Barnyardgrass	0	0	0	5	0	0	0	0	0	0.08	0	0	0.62
Elymus repens (L.) Gould	Quackgrass	0	0	0	0	0	5	0	0	0	0	0	0.03	0.65
Erodium cicutarium (L.) L'Her. ex Ait.	Redstem filaree	0	0	7	0	0	0	0	0	0.06	0	0	0	0.41
Galium aparine L.	Catchweed bedstraw	0	0	0	0	0	10	0	0	0	0	0	0.25	0.58
Geum spp.	Avens	11	0	0	0	0	0	2.6	0	0	0	0	0	0.37
Hordeum brachyantherum Nevski	Meadow barley	5	0	0	0	0	0	1.0	0	0	0	0	0	0.58
Hordeum jubatum L.	Foxtail barley	11	45	0	0	0	0	0.16 a	6.0 b	0 a	0 a	0 b	0 a	**0.01**
Hordeum murinum L. ssp. *leporinum* (Link) Arcang.	Hare barley	0	0	13	25	0	0	0	0	0.15	23	0	0	0.20
Hordeum vulgare L.	Barley	16	100	0	0	0	10	0.22 a	45 b	0 a	0 a	0 a	0.06 a	**< 0.001**
Juncus bufonius L.	Toad rush	0	0	0	0	33	0	0 b	0 b	0 b	0 b	0.52 a	0 b	**< 0.0001**
Lactuca serriola L.	Prickly lettuce	0	0	7	0	0	14	0	0	0.08	0	0	0.68	0.58
Leontodon autumnalis L.	Fall hawkbit	11	9	0	0	0	10	9.8	0.06	0	0	0	0.08	0.37
Lolium perenne L.	Perennial ryegrass	0	0	0	0	17	10	0 b	0 b	0 b	0 b	76 a	0.04 b	**0.01**
Lolium perenne L. ssp. *multiflorum* (Lam.) Husnot	Italian ryegrass	0	0	0	5	83	10	0 b	0 b	0 b	0.03 b	1022 a	0.11 b	**< 0.001**
Matricaria discoidea DC.	Pineapple-weed	5	0	0	0	0	0	0.10	0	0	0	0	0	0.58

Table 1. Continued.

		Frequency of occurrence						Mean number of seeds						
		Alaska		WA–OR				Alaska		WA–OR				ANOVA
Scientific name	Common name	TBH	BS	AH	TH	RS	WS	TBH	BS	AH	TH	RS	WS	Pr > F
Phleum pratense L.	Timothy	63	18	7	75	0	14	651 a	3.8 b	0.08 b	151 a	0 ab	0.39 b	**0.006**
Plantago major L.	Broadleaf plantain	11	0	0	5	0	0	0.08	0	0	0.05	0	0	0.52
Poa annua L.	Annual bluegrass	0	18	0	0	17	14	0	0.54	0	0	0.34	1.1	0.51
Poa compressa L.	Canada bluegrass	0	0	0	0	0	5	0	0	0	0	0	1.5	0.52
Poa glauca Vahl	Glaucous bluegrass	0	9	0	0	17	5	0	0.07	0	0	0.20	0.08	0.39
Poa palustris L.	Fowl bluegrass	32	27	7	15	0	10	629	0.36	0.30	1.2	0	1.6	0.11
Poa pratensis L.	Kentucky bluegrass	26	9	0	5	17	5	10	0.33	0	3.8	0.17	0.02	0.21
Poa spp.	Bluegrass	16	0	7	0	0	5	72	0	0.11	0	0	0.03	0.48
Polygonum aviculare L.	Prostrate knotweed	5	0	0	0	0	0	0.06	0	0	0	0	0	0.58
Polygonum convolvulus L.	Wild buckwheat	0	18	0	0	0	0	0	0.92	0	0	0	0	0.11
Potentilla norvegica L.	Rough cinquefoil	5	0	0	5	0	0	0.10	0	0	0.06	0	0	0.72
Ranunculus macounii Britton	Macoun's buttercup	0	0	0	0	17	0	0 a	0 a	0 a	0 a	0.85 b	0 a	**0.01**
Salix spp.	Willow	58	64	7	40	67	43	2.7	0.82	0.06	0.62	1.9	0.46	0.19
Senecio vulgaris L.	Common groundsel	0	0	0	20	0	5	0	0	0	1.3	0	0.04	**0.03**
Setaria viridis (L.) Beauv.	Green foxtail	0	0	0	15	0	10	0	0	0	58	0	0.25	0.07
Sisymbrium altissimum L.	Tumble mustard	0	0	0	0	0	5	0	0	0	0	0	0.01	0.65
Sonchus asper (L.) Hill	Spiny sowthistle	0	0	13	5	0	38	0	0	0.14	0.28	0	1.2	0.28
Spergula arvensis L.	Corn spurry	26	0	0	5	0	0	0.51	0	0	0.06	0	0	**0.04**
Stellaria media (L.) Vill.	Common chickweed	5	27	0	20	0	10	0.93	0.54	0	0.59	0	0.07	0.73
Taraxacum officinale G.H. Weber ex Wiggers	Dandelion	42	9	20	25	17	14	49	0.04	0.33	0.17	0.75	0.08	0.24
Trifolium repens L.	White clover	11	0	0	5	0	0	1.8	0	0	0.17	0	0	0.38
Triticum aestivum L.	Wheat	5	0	7	5	0	95	0.05 a	0 a	0.15 a	0.01 a	0 a	39 b	**< 0.0001**
Unknown broadleaf		26	9	7	20	0	24	0.30	0.04	0.10	0.35	0	0.12	0.38
Unknown grass		5	0	0	5	0	0	0.41	0	0	0.13	0	0	0.68

[a] Abbreviations: TBH, timothy/brome hay (n = 19); BS, barley straw (n = 11); AH, alfalfa hay (n = 15); TH, timothy hay (n = 20); RS, ryegrass straw (n = 6); WS, wheat straw (n = 21); WA–OR, Washington and Oregon.

[b] Mean number of seeds for each species with different letters are significantly different between the crop types according to Tukey's HSD (P ≤ 0.05).

[c] Bold indicates statistical significance (P ≤ 0.05).

straw, and dyer's woad (*Isatis tinctoria* L.) and lens-podded whitetop [*Cardaria chalapensis* (L.) Hand.-Maz.] established at pack stations.

Very few studies of weed contamination in hay and straw have been published. Thomas et al. (1984) examined 38 bales of hay that were being shipped to New South Wales from other parts of Australia because drought limited the amount of local hay. Gower (2008) obtained hay or hay-substitute samples from owners of horses competing in American Endurance Ride competitions. The samples were assessed for weed contamination by mixing the samples with potting soil and incubating this mixture in pots outside. Three weed species were found germinating from the hay samples: Canada thistle, musk thistle (*Carduus nutans* L.), and giant foxtail (*Setaria faberi* Herrm.). It should be noted that the horses that compete in the American Endurance Ride are elite animals, fed the highest quality hay possible, and that lesser quality feed could contain more weed contaminants.

The objectives of the study were to determine (1) the retail sources and amounts of hay and straw imported to Alaska and (2) the identity and amounts of weed seed contaminants in hay and straw from locally produced and imported hay and straw.

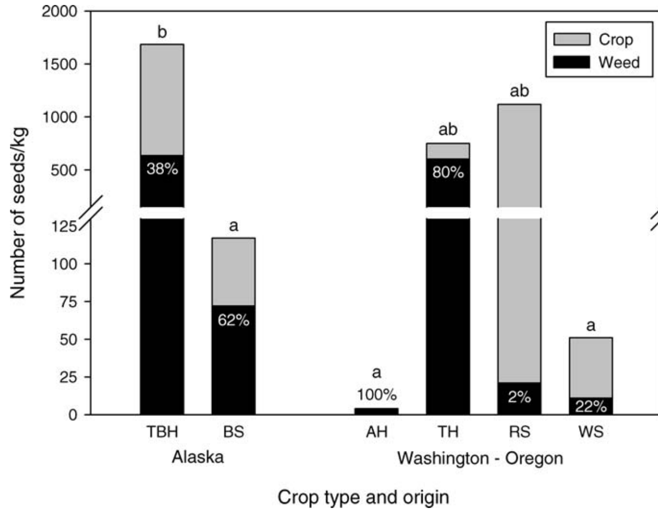

Figure 1. Mean number of crop and weed seeds found in locally grown and imported hay and straw. TBH, timothy/brome hay (n = 19); BS, barley straw (n = 11); AH, alfalfa hay (n = 15); TH, timothy hay (n = 20); RS, ryegrass straw (n = 6); WS, wheat straw (n = 21). Different letters indicate statistical significance among crop types for total number of seeds (crop + weed). Percentages indicate the proportion of weed seeds in the total number of seeds found in each crop type.

Materials and Methods

Hay and Straw Sales Survey. Feed stores, farms, and trucking companies selling or importing hay and straw in Alaska were identified through the State of Alaska Division of Agriculture Food and Farm Product Directory (Anonymous 2007). We also contacted Cooperative Extension Service agents in Fairbanks, Delta Junction, and Anchorage to identify additional vendors and growers of hay and straw not listed in the directory.

During 2004 and 2005, we visited feed stores and contacted farmers, stables, and trucking companies that imported, grew, or sold hay and straw in the Anchorage and Matanuska Valley area (n = 19), Fairbanks (n = 20), Delta Junction (n = 2), and Kenai Peninsula (n = 11). We interviewed owners or managers to determine (1) the amount and species of hay and straw sold and (2) the name of the grower or distributor and the origin of the hay or straw, and (3) the total weight of each hay or straw species imported from each grower or distributor each year. Fifty-two vendors of hay and straw were contacted.

Greenhouse Germination Study. We used the vendor survey data to develop a shopping list that captured the range of hay and straw species and growers without duplicating the same offerings from different vendors. Three bales were purchased of each crop species from each grower, totaling 96 bales and comprising 14 Alaska and 18 out-of-state hay or straw sources. The out-of-state bales were all from Washington and Oregon (WA–OR) and the 14 in-state bales were from Delta Junction, Copper Center, Fairbanks, Wasilla, Trapper Creek, and Point Mackenzie. The bales were tagged and placed in large plastic bags to preclude seed rain before analysis.

The mass of each bale was determined and one-fourth of each bale was analyzed. Hay and straw samples were shaken over a table covered in 6- by 6-mm hardware cloth, and the resulting fines were collected and then passed through a 3- by 3-mm screen. The material passing through this screen was collected and weighed.

Preliminary work determined that it was very difficult to separate seeds from the fine organic matter present in the screenings. Instead of separating seed from the organic debris, we incubated the soil in a greenhouse to determine the species and numbers of germinants grown from the seeds in the hay and straw bales. Two 40-g samples of fines from each bale were each mixed with 750 g of sterile potting soil and placed in a 2-cm-thick layer in separate 56- by 41-cm trays in a heated greenhouse beginning June 5, 2006. Four trays with sterile potting soil only were placed at various locations in the greenhouse to act as controls for the possible airborne addition of seeds. Temperatures in the greenhouse ranged from 15 to 35 C, and the day length was 16 to 22 h. Trays were kept moist, which usually entailed daily watering with a fine spray. Seedlings in each tray were counted weekly by type. Photographs of each tray were taken every few weeks to aid in tracking development of different seedling types. Samples of each seedling type

Table 2. Mean number of seeds and species per bale found in hay and straw locally produced in Alaska (n = 30) and imported from Washington and Oregon (WA–OR, n = 62).[a]

Origin	Total seed	Weed seed	Total species	Weed species
	No. seeds kg^{-1}		No. species	
Alaska	1,110 a	430	3.7 a	2.9 a
WA–OR	368 b	201	2.8 b	2.1 b
ANOVA P > F	0.014	0.244	0.031	0.035

[a] Means within a column that do not share the same letter are significantly different (P ≤ 0.05) according to Tukey's HSD.

from each tray were transplanted into pots so that they could be grown until they could be identified, and a voucher specimen of each species was made.

All trays were counted by seedling type and were harvested on July 31, 2005. The trays were allowed to dry, and on August 21, 2006, the trays were stirred and rewatered, and additional seedlings in each tray were recorded weekly until germination in all trays ceased on September 28, 2006.

Statistical Analysis. Seedling count data for the two trays were averaged for each bale and were converted to total seedlings per bale and total seeds per kilogram of hay or straw. To determine the effects of origin (WA-OR vs. Alaska), crop species, and source (grower or distributor) on number of seeds and number of species in hay and straw, we analyzed the data with a series of one-way ANOVAs (PROC GLM of SAS[1]). It was not possible to analyze the data with multiple independent variables because the design was not balanced. Tukey's HSD was used to separate means. All data were square root–transformed before analysis to satisfy assumptions of normality and homogeneity of variances, but data presented in tables are not transformed.

We used indicator species analysis in PC-ORD[2] to identify individual weed species associated with each crop type and the origin of the hay and straw. Indicator values (IV_{jk}) were calculated as

$$IV_{jk} = 100\ (A_{jk} \times F_{jk}), \qquad [1]$$

where A_{jk} and F_{jk} are the relative abundance and relative frequency, respectively, of species j in group k (Dufrêne and Legendre 1997; McCune and Grace 2002). Indicator values range from 0 (no association) to 100 (perfect association to a group). Statistical significance of the maximum indicator value for each species was determined by 1,000 iterations of a Monte Carlo randomization test. Indicator values were calculated for each species on untransformed seed density data. Separate analyses were performed for the groups of crop type and origin of hay and straw.

Results and Discussion

Hay and Straw Sales Survey. Thirty-three (72%) of the businesses contacted provided information on whether they

Table 3. Mean number of seeds and species per bale in hay and straw in six crop types.[a,b]

Crop type	Total seed	Weed seed	Total species	Weed species
	No. seeds kg^{-1}		No. species	
Alaska				
Timothy/brome hay (n = 19)	1,684 b	636	3.5 b	2.8 b
Barley straw (n = 11)	117 a	72	4.0 b	3.0 b
WA–OR				
Alfalfa hay (n = 15)	3 a	3	1.2 a	1.2 a
Timothy hay (n = 20)	749 ab	602	3.3 b	2.6 b
Ryegrass straw (n = 6)	1,119 ab	21	3.0 b	2.0 ab
Wheat straw (n = 21)	51 a	11	3.3 b	2.3 ab
ANOVA P > F	0.0004	0.060	0.0008	0.021

[a] Abbreviation: WA–OR, Washington and Oregon.

[b] Means within a column that do not share the same letter are significantly different (P ≤ 0.05) according to Tukey's HSD.

Table 4. The effect of grower or distributor on mean seeds and species per bale contained in locally grown or imported hay and straw.[a,b]

Crop type	Grower or distributor	Total seed	Weed seed	Total species	Weed species
		——No. seeds kg^{-1}——		——No. species——	
Alaska					
Timothy/brome hay	1	129 a	32	2.8 a	1.8 a
	2	200 a	3	1.8 a	0.8 a
	3	22 a	22	2.7 a	2.7 a
	4	5019 b	2793	3.8 a	3.7 a
	5	13 a	7	2.0 a	1.3 a
	6	2187 ab	4	3.5 a	2.5 a
	7	4655 ab	1759	9.0 b	8.0 b
WA–OR					
Alfalfa hay	1	2 a	2 a	0.6 a	0.6 a
	2	2 a	2 a	0.8 a	0.8 a
	3	9 b	9 b	3.0 b	3.0 b
Timothy hay	1	913 b	741 b	4.0 ab	3.0 abc
	2	506 a	276 a	2.2 ab	1.2 a
	3	216 a	208 ab	5.5 c	4.8 c
	4	3065 c	3018 c	4.7 b	4.3 c
	5	19 a	19 ab	1.8 ab	1.8 ab
	6	12 a	5 a	2.5 ab	1.7 a
	7	270 a	29 a	2.2 ab	1.2 a
Wheat straw	1	69	19	5.1 bc	4.1 b
	3	75	16	2.8 a	1.8 a
	3	38	16	2.5 ab	1.8 ab
	4	18	11	2.3 a	1.3 a
	5	13	11	2.3 a	1.3 a

[a] Abbreviation: WA–OR, Washington and Oregon.

[b] Means within a column in each crop type that do not share the same letter are significantly different ($P \leq 0.05$) according to Tukey's HSD.

sold hay and straw and 16 of these businesses (48%) reported that they sold hay and straw that was imported into Alaska from WA–OR. Only seven businesses were willing to give information on the amounts of hay and straw they imported. The total hay and straw imported by these businesses in 2004 was 240 metric tons (mt) alfalfa hay, 305 mt timothy hay, 94 mt of wheat (*Triticum*) straw, and 18 mt of ryegrass (*Lolium*) straw. This compares with the 2004 local hay and straw production of 25,673 mt timothy/brome hay and 635 mt barley straw (Benz et al. 2005).

It was not possible to identify farms from which the hay and straw originated. The local vendors generally buy from large distributors who, in turn, buy or produce hay and straw from multiple farms and do not provide information on farm source. Some trucking companies buy hay and straw from individual farms, but declined to provide exact sources.

Greenhouse Germination Study. No seeds germinated in the control trays, showing that airborne seed contamination was not a problem during the greenhouse incubation period. Forty-nine different species germinated from the hay and straw samples (Table 1). We were able to identify most of the seedlings, but a few transplants died before they were identifiable. These seedlings were classified as unknown broadleaves (0.03% of total germinants) and unknown grasses (0.02% of total germinants). In addition, some of the bluegrass and willow (*Salix* spp.) germinants were not identifiable to the species level (2.5 and 0.2% of total germinants, respectively). We were able to identify 97.2% of all germinants to the species level.

As was the case for the study of Australian hay and straw (Thomas et al. 1984), variability in the number of germinable seed recovered was quite high among bales from the same supplier, reflecting intra- and interfield variation in weed density and composition. Several bales of alfalfa hay contained 0 germinable seed, whereas the greatest number of weed seed (6,205 seeds kg^{-1}) was found in a bale of Alaska timothy/brome hay. An average of 585 seeds kg^{-1} was found over all bales in the study. The number of weed species per bale from the hay and straw samples ranged from 0 (alfalfa) to 12 (Alaska timothy/brome hay), with an average of 4.2 species per bale. Seed of crop species comprised an average of 44% (260 seeds kg^{-1}) of the germinated seeds found in all hay and straw bales. Crop seed comprised a large proportion of the germinated seeds in ryegrass straw, wheat straw, and timothy/brome hay (98, 78, and 62%, respectively; Figure 1). The proportion of crop seed was less prevalent in alfalfa hay (0%), timothy hay (20%), and barley straw (38%). The number of seeds in this study were more than four times lower than those found in the Australian study (4 to 14,000 seeds kg^{-1} and an average of 2,640 seeds kg^{-1}; Thomas et al. 1984).

Hay and straw from Alaska contained significantly more seeds and species than hay and straw from WA–OR, but there was no difference when only weed (noncrop) seeds and species were used in the analysis (Table 2). Additionally, the number of seeds and number of species differed among crop types (Figure 1; Table 3). Alfalfa hay, wheat straw, and barley straw contained significantly fewer seeds than timothy/brome hay. There was a trend for timothy/brome hay in Alaska and timothy in WA–OR to have more weed seed and alfalfa to have less. Alfalfa hay had significantly fewer species than every other crop type, although these differences were not always significant when only weed species were used in the analysis. Species richness (not including unknown broadleaf and grass species) for each crop type was highest in WA–OR wheat straw and timothy hay (30 and 25 species, respectively) and Alaska timothy/brome (27) and was lower in Alaska barley straw (17) and WA–OR alfalfa hay and ryegrass straw (both 14 species).

The grower or distributor that produced or brokered the hay and straw also affected the number of total and weed seeds (one-way ANOVA, $P \leq 0.05$; Table 4) for WA–OR alfalfa and timothy hay and Alaska timothy/brome hay, reflecting differences between sources in weed management and other farming practices. The number of total and weed species contained in all crops except ryegrass and barley straw was also affected by the grower or distributor (Table 4).

Individual weed species identified differed among crop types and among the origin (Alaska or WA–OR) of hay and straw (Table 1). Twenty weed species were only found in hay and straw bales grown in WA–OR and were not found in bales produced in Alaska. These weed species were: downy brome (occurring in 37% of WA–OR bales), spiny sowthistle [*Sonchus asper* (L.) Hill; 18%], redroot pigweed (*Amaranthus retroflexus* L.; 15%), flixweed [*Descurainia sophia* (L.) Webb. ex Prantl; 13%], hare barley ([*Hordeum murinum* L. ssp. *leporinum* (11%), common groundsel (*Senecio vulgaris* L.; 8%), green foxtail [*Setaria viridis* (L.) Beauv.; 8%], prickly lettuce (*Lactuca serriola* L.; 6%), mayweed chamomile (*Anthemis cotula* L.; 5%), and 11 other species with frequency of occurrence $< 5\%$. Quackgrass [*Elymus repens* (L.) Gould; 2%] is listed as a prohibited species in Alaska, and downy brome and hare barley are listed as invasive species in Alaska (Carlson et al. 2008). The other species are significant agricultural weeds elsewhere and could be a threat to Alaskan agriculture.

Ten weed species only occurred in Alaska-grown hay and straw: foxtail barley (*Hordeum jubatum* L.; occurring in 23% of Alaska bales), rough bentgrass (*Agrostis scabra* Willd.; 17%), narrowleaf hawksbeard (*Crepis tectorum* L.; 7%), avens (*Geum* spp.; 7%), wild buckwheat (*Polygonum convolvulus* L.; 7%), and five other species with frequency of occurrence $< 5\%$. Foxtail barley and narrowleaf hawksbeard are ranked as invasive species in Alaska (Carlson et al. 2008). Foxtail barley was found in 45% of the barley straw and 11% of the timothy/brome hay bales sampled. This species has barbed awns and can cause mouth ulcers and abscesses in livestock and dogs that consume it (Kahn 2005). Consumers in Alaska sometimes purchase imported hay and straw to avoid problems with foxtail barley.

Indicator species were identified for all but one crop type. Four indicator species were identified in both barley straw and timothy hay, three indicator species in timothy/brome hay, one indicator species in both ryegrass straw and wheat straw, and no indicator species in alfalfa hay. Dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers; 41% of perfect indication), fowl bluegrass (*Poa palustris* L.; 31%), and corn spurry (*Spergula arvensis* L.; 24%) were strongly associated with timothy/brome hay. Foxtail barley (44%), rough bentgrass (25%), narrowleaf hawksbeard (18%), and wild buckwheat (18%) were strongly associated with barley straw. Downy brome (43%), shepherd's-purse [*Capsella bursa-pastoris* (L.) Medik.; 40%], hare barley (25%), and common groundsel (19%) were strongly associated with timothy hay. Toad rush (*Juncus bufonius* L.; 33%) was strongly associated with ryegrass straw. Spiny sowthistle (28%) was strongly associated with wheat straw. Of the 49 species identified in this study, 13 (27%) were an indicator species of one of the crop types. No indicator species were common among different crop types.

Indicator species were also identified by the origin of hay and straw. Hay and straw from Alaska had seven significant indicator species, whereas samples from WA–OR had only two indicator species. Significant indicator species from Alaska hay and straw included willow (47%), dandelion (30%), fowl bluegrass (30%), foxtail barley

(23%), Kentucky bluegrass (*Poa pratensis* L.;17%), rough bentgrass (17%), and corn spurry (16%). Dandelion and Kentucky bluegrass are ranked as invasive species in Alaska (Carlson et al. 2008). Significant indicator species from WA–OR hay and straw included downy brome (37%) and spiny sowthistle (18%). Of the 49 species identified in this study, only 9 (18%) were a significant indicator species for one of the hay and straw origins. No indicator species were common among the different origins of hay and straw.

Pathway Risk. Characterizing the overall size of imported hay and straw movement as a pathway for weed dispersal is made difficult by the incomplete survey results and the assumption that the samples we analyzed typify the pathway. If only the reported hay and straw sales are used and the assumption is made that the samples are typical of all hay and straw sold, there were 5,640 quackgrass, 36.9 million downy brome, and 13.8 million hare barley seeds imported into Alaska with hay and straw. With the use of data from Benz et al. (2008) for the amounts of hay and straw grown in Alaska, 10.8 million foxtail barley and 3.9 million narrowleaf hawksbeard seed could have been dispersed with locally produced hay and straw.

On the basis of our results, large numbers of alien plant species are transported by movements of hay and straw into and within Alaska, thus exerting a large amount of propagule pressure. However, the overall strength of a particular pathway also depends on the likelihood of a species establishing once it arrives at a new location (Mack 2003; Ruiz and Carlton 2003). Several studies have been conducted to evaluate the importance of horses and associated feeds in dispersing exotic plants into new areas along trails. Marcus et al. (1998) studied patterns of spotted knapweed (*Centaurea stoebe* L.) distribution in stock camps, campsites, and along trails in the Selway–Bitterroot Wilderness Area in Montana and Idaho and determined that spotted knapweed population levels were correlated with site disturbance and canopy cover, but not with pack animal use. Gower (2008) placed hay at various distances perpendicular to horse trails and determined the percent germination and survival. Nonnative plants grew from only a few plots, and none survived more than a year. Although germination and survival of species arriving in undisturbed sites might be low, a high amount of propagule pressure increases the likelihood of a population establishing. In Alaska, foxtail barley is known to have established at 9 of 14 checkpoints surveyed along the Iditarod Trail from straw used to bed sled dogs during the Iditarod Sled Dog Race (Flagstad et al. 2009). Although establishment in undisturbed sites might be rare, hay and straw are also used in paddocks and dog kennels where soil fertility and disturbance are high and should favor establishment of the seed contaminants.

The size of the hay and straw pathway for introduction of new alien plant species to Alaska and subsequent spread could be greatly reduced if growers would use the most effective weed control practices to minimize seed contamination. Vendors could help to reduce this pathway by buying NAWMA-certified weed-free forage or by personally inspecting fields to ensure that weeds are not present.

Sources of Materials

[1] SAS, Version 9.2, SAS Inc., Campus Drive, Cary, NC 27513.

[2] PC-ORD Multivariate Analysis of Ecological Data, Version 4, MjM Software Design, P.O. Box 129, Gleneden Beach, OR 97388.

Acknowledgments

We thank U.S. Forest Service State and Private Forestry for helping to fund this research. Michael Shephard helped shape the study design. Kate Beattie identified some of the plant specimens.

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Received November 09, 2009, and approved April 16, 2010.